Impact of Stream Hardening on Water Quality and Metabolic Characteristics of Waimānalo and Kāne'ohe Streams, O'ahu, Hawaiian Islands[1]

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Abstract: Kāne'ohe and Waimānalo Streams on the windward side of the island of O'ahu in the Hawaiian Islands have been hardened to prevent flooding. The hardening process has involved elimination of the natural riparian habitat and replacement of the natural stream channel with a concrete-lined conduit having vertical walls and a broad, flat bottom. The shallow depth of the water column and absence of shade have resulted in temperatures that average as much as 4–5°C above ambient and rise as high as 32°C during daylight hours. Unlike most low-order streams, the hardened sections of both streams are autotrophic, as evidenced by elevated pH values and O_2 concentrations as high as 150% of saturation. Several allochthonous inputs, one from a storm sewer and the other from a natural spring, introduced water with anomalously low O_2 concentrations and very high nitrate concentrations. The absence of sediments in the hardened sections of the streams precludes natural sedimentary microbial processes, including denitrification. Nitrate concentrations in a section of Waimānalo Stream with a natural streambed drop dramatically from values in excess of 400 μM to concentrations less than 10 μM at the head of the estuary. Although some of this decline is due to dilution with seawater, the concentration of nitrate at the head of the estuary is only 10% of the value that could be explained by dilution effects. Biological processes associated with a natural streambed thus appear very important to functionality of the streams and in particular to their ability to process allochthonous nutrient inputs in a way that minimizes impacts on the nearshore environment. Prevention of flooding can be accomplished by mechanisms that do not involve elimination of riparian buffer zones and destruction of channel habitat. To maintain water quality and stream functionality, it is important that these alternative methods of flood control be utilized. Converting natural streams to storm sewers is an unenlightened way to address flooding problems.

DESPITE SUCCESSFUL EFFORTS to reduce point-source pollutants in the United States since the passage of the Clean Water Act, nonpoint source pollution, including eutrophication and sedimentation, remains a substantial threat to coastal ecosystems, especially coral reefs (Bryant et al. 1998). Much of the focus of environmental remediation concerned with nonpoint source pollution has targeted fluxes of nutrients and sediments (Environmental Protection Agency 1999*a,b*), but in some cases the important stressor agents are direct manipulations of the physical habitat via riparian modification, dredging, and channelization (Rankin et al. 1999:33). As noted by Rankin et al. (1999:39), "Meeting Clean Water Act goals will likely be frustrated without consideration of the critical role of riparian and instream habitat."

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Several considerations underlie this conclusion. Anthropogenic modifications of stream habitat generally include one or more of the following factors: (1) hardening of the stream channel in the name of flood control, (2) reduction or debilitation (in terms of width or function) of the riparian buffer zone to accommodate urban development or other human activities, and (3) reduction of flow for irrigation purposes. Poor-quality lotic habitat with a nonexistent or dysfunctional riparian buffer zone and simplified channel morphology generally exacerbate the deleterious effects of residual nutrient concentrations by (1) reducing the riparian uptake and conversion of nutrients, (2) increasing nutrient retention times through increased sediment–water column interface via a wide channel and subsequent loss of low-flow energy (e.g., increased intermittency), (3) increasing the retention of nutrients within the channel due to diminished filtering time during overland flow events, and (4) allowing full sunlight to stimulate nuisance growth of algae (Rankin et al. 1999:9). Typical hardened streams with flat concrete bottoms and rectangular or trapezoidal cross sections with little or no riparian vegetation (Figure 1) provide a uniform habitat in which daytime temperatures are unusually high due to the absence of shade and the shallow depth of the water column (Dashiell 1997). The uniform and extreme conditions in this habitat are typically associated with a biological community having little diversity (May 1974) and dominated by species able to tolerate the stressful environment. A diverse and high-quality biological community sequesters nutrients by processing and partitioning them between a variety of species and trophic levels, and thereby acts to mute episodic downstream transport (Rankin et al. 1999:14). The simple biological assemblage of stress-tolerant species characteristic of a hardened stream lacks this capability and therefore exacerbates eutrophication problems. The presence of an active microbial community in stream sediments is especially important in the case of nitrogen, because the sediments are the primary site of denitrification and the rate of denitrification increases in the presence of organic biomass such as leaf litter (Rankin et al. 1999:32). The paucity of sediment in a concrete-lined channel and the absence of overhanging vegetation in a stream lacking riparian habitat greatly reduce the potential for denitrification in a typical hardened stream.

In Hawai'i stream habitat modifications have occurred on a large scale. Of 61 Hawaiian streams investigated by Wolinsky and Palomino (1996) as part of the state's efforts to comply with the Clean Water Act (Henderson and Harrigan 2002), the channels of 42 were judged to have been hardened with concrete or substantially modified or straightened, and the riparian habitats of 41 were judged to have been cleared of vegetation. In the Lahaina District of West Maui only one stream, Honokōhau, discharges to the ocean during dry weather. The remaining 10 streams that drain the watershed were diverted for irrigation of sugarcane more than 100 yr ago and today discharge only during periods of heavy rainfall (Soicher and Peterson 1997). In virtually all cases these habitat modifications are the result of efforts to control flooding and/or provide water for irrigation. There is no doubt that these habitat modifications have had a devastating impact on water quality and stream functionality. As noted by Harrigan and Burr (2001:14) in the case of Waimānalo Stream, "Regardless of how many BMPs [best management practices] are implemented for sediment and nutrient control, significant improvement in the water quality of Waimānalo Stream will be difficult to achieve unless in-stream standards for flows are set to increase the base flow and stream channels and riparian wetlands are at least partly restored to their natural form and function." Their assessment with respect to Waimānalo Stream is echoed in a more general context by Rankin et al. (1999:45), who commented, "Upland BMPs will have few realized benefits if habitat restoration is not included." These conclusions have important implications for the efforts of the U.S. Environmental Protection Agency to control nutrient and sediment fluxes through the so-called total maximum daily load (TMDL) process (Reckhow et al. 2001). As noted by

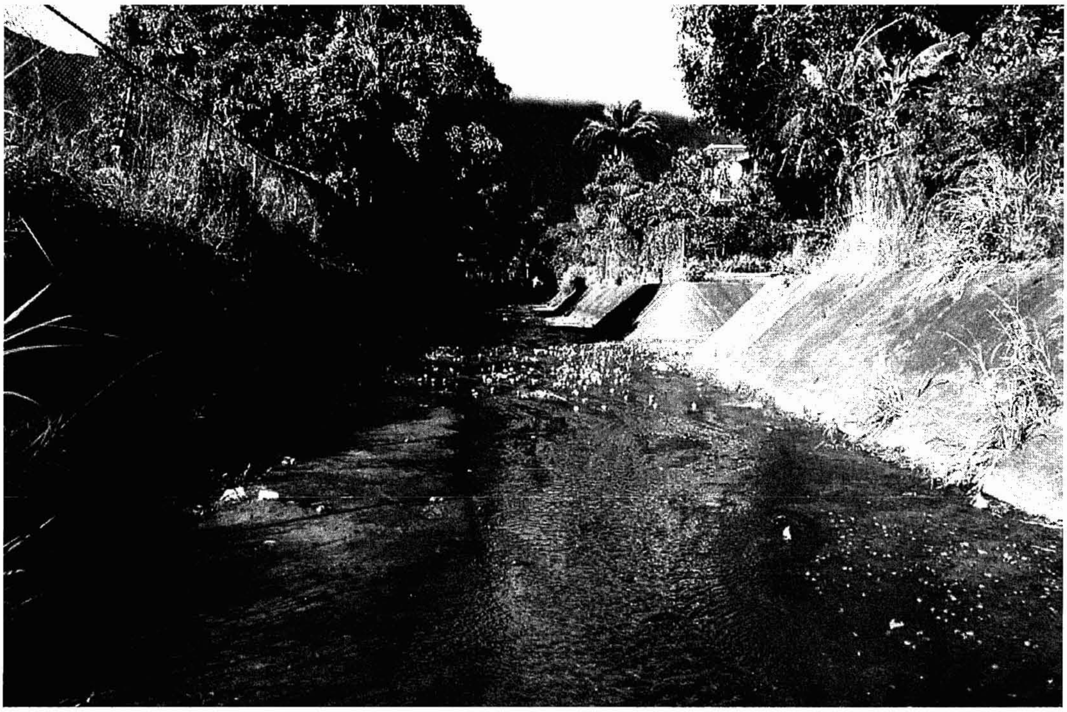

FIGURE 1. Hardened section of the Kahawai tributary of Waimānalo Stream near sampling station 5.

Reckhow et al. (2001:10), the Clean Water Act recognizes that pollution includes conventional pollutants as well as other stressors such as habitat destruction and hydrologic modifications. "Given their demonstrated effectiveness, activities that can overcome the effects of 'pollution' and bring about waterbody restoration—such as habitat restoration and channel modification—should not be excluded from consideration during TMDL plan implementation (Reckhow et al. 2001:3).

The study reported here targeted two modified streams in Hawai'i, Waimānalo Stream and Kāne'ohe Stream (Figures 2 and 3). Sections of both streams have been hardened, and the primary goal of the study was to quantify the effects of this hardening on water quality and stream functionality. The study is ongoing, and the results reported here represent initial work carried out during 2002 with support from the Hawai'i Coral Reef Initiative Program.

Stream and Watershed Characteristics

The Waimānalo Stream watershed covers an area of 15.3 km^2 on the windward side of the island of O'ahu in the Hawaiian Islands (Figure 2). The watershed is drained by Waimānalo Stream, which originates on the eastern side of the Ko'olau mountain range. The stream consists of two principal tributaries, Waimānalo Stream to the north and Kahawai Stream to the south. The two streams merge roughly 0.5 km below Kalaniana'ole Highway (Figure 2). The stream enters the ocean at Bellows Beach about 2 km below the confluence of the two tributaries. The distance from the headwaters to the mouth of the stream is approximately 5.5 km. Annual discharge is estimated to be 1.0×10^7 m^3 (Laws and Ferentinos 2003).

From the late nineteenth to the mid-twentieth centuries a series of water diversions, including dams in the stream and a

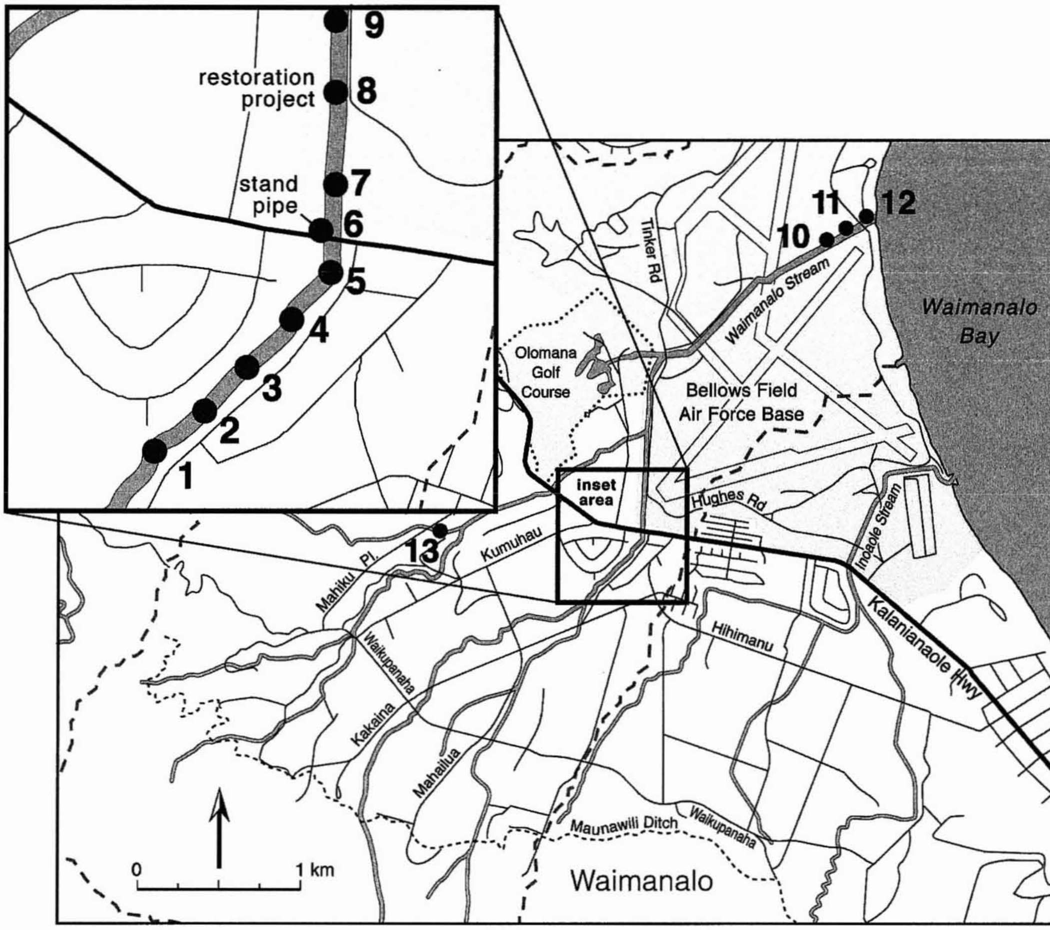

FIGURE 2. Waimānalo watershed and sampling stations. Data collected from station 13 were not included in this analysis.

network of irrigation ditches, facilitated the cultivation of sugarcane. When sugarcane cultivation ended in the mid-1940s, the land was broken up into nurseries, livestock, and truck farms (Bartholomew and Associates 1959). Increasing urbanization along the highway resulted in channelization of portions of the streams in the 1960s to avert flooding of the small subdivision lots. Development of runways on the military base and the construction of Olomana Golf Course (Figure 2) drained the lower wetland areas, changed the course of the stream, and eliminated the lagoon that previously existed at the mouth of the stream (Sustainable Resources Group International 2001).

Recent land use in the watershed has been the subject of a study by the Hawai'i Department of Health (1998) and Kihara (2001). Based on zoning maps, Kihara estimated the land to be about 3% urban, 48% conservation or steeply sloping, and 49% agricultural. The higher-elevation portions of the watershed are entirely in the conservation/steeply sloping category, where the slopes of the fluted cliffs (pali) range from 45° to nearly 85° and are steepest between altitudes of 200 and 450 m. A talus slope generally obscures the lower

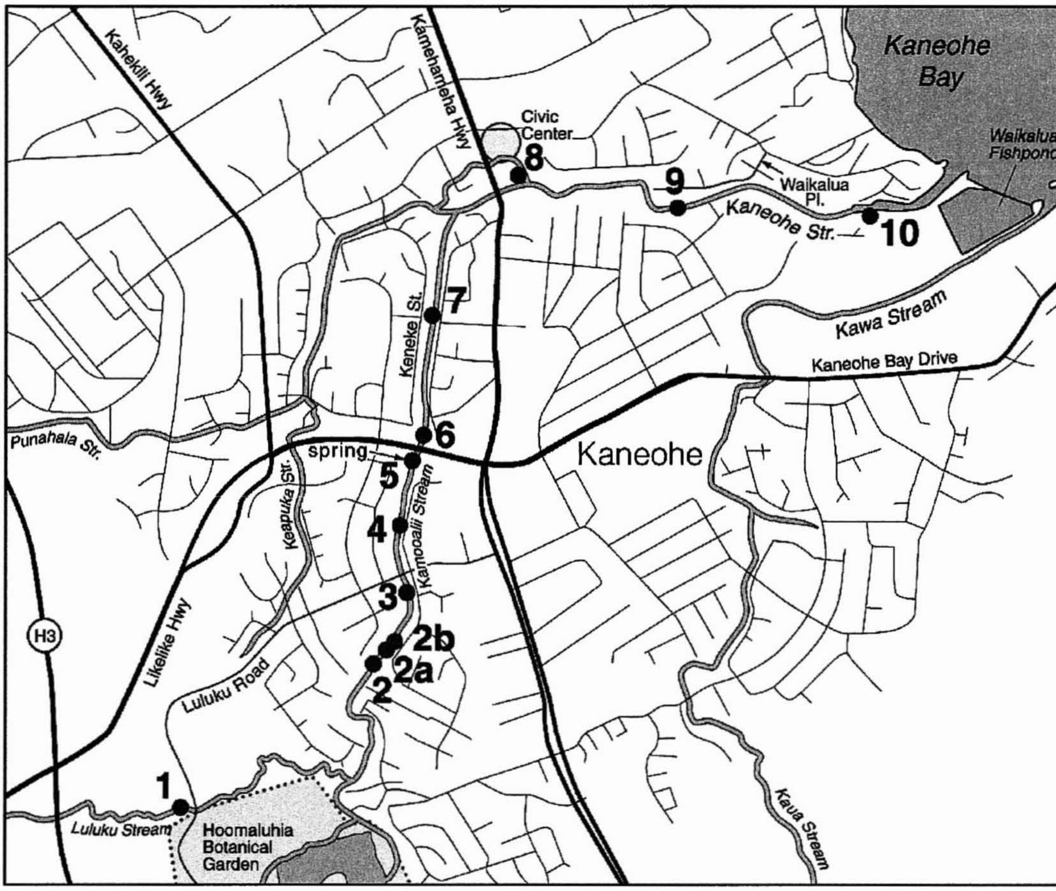

FIGURE 3. Kāne'ohe watershed and sampling stations. Data collected from stations 2a and 2b were not included in the analysis.

parts of the cliffs below an altitude of 200 m (Takasaki et al. 1969). The City and County of Honolulu zoning classifications designate land use in the watershed as 54% preservation, 41% agriculture, 3% country, and 2% residential (Hawai'i Department of Health 1998). The preservation category includes both conservation and military lands. The latter includes Bellows Field Air Force Base, which, together with the Olomana Golf Course, accounts for all the lowest-elevation land in the watershed (Figure 2). The mountainous preservation land is largely undeveloped. During the era of sugarcane cultivation in the watershed, a water diversion system known as the Maunawili Ditch was used to intercept stream runoff within the preservation land and route that runoff to sugarcane fields. Its use for that purpose ceased during the mid-1940s. From that time until 1955 the Maunawili Ditch was used to provide irrigation water for diversified agriculture. The ditch ceased to play a role in agriculture in 1955. At the current time runoff intercepted by the ditch is transported to the nearest stream. About 2.4 km^2 of Bellows land is used for military training exercises, and there is some helicopter training on part of an abandoned runway. There is a beach park along the seashore and some recreational cabins and campgrounds. Sanitary facilities for the cabins and campgrounds are serviced by cesspools,

FIGURE 4. Wild sugarcane and California grass in the Kahawai tributary of Waimānalo Stream.

which may seep into the nearshore ocean but have no potential to impact Waimānalo Stream.

The human impact on land use has been primarily on the agricultural land. About 47% of the agricultural land is used for livestock grazing (Laws and Ferentinos 2003). The livestock population has been estimated to include 321 horses, 550 hogs, 62 cattle, and 2803 chickens (Medeiros 1998). Using typical animal excretion rates (Medeiros 1998) these animals are estimated to produce about 29 t of nitrogen and 7 t of phosphorus per year. Ninety percent of the hog population is located at a single facility on Waikupahana Street between Kaka'ina and Kumuhau Streets (Figure 2). The remaining population of livestock is scattered widely throughout the watershed between Kalaniana'ole Highway and the Ko'olau Mountains (Medeiros 1998).

Waimānalo Stream is a highly altered waterway that in many respects no longer functions as a stream (Harrigan and Burr 2001). Stream channels have been heavily modified over the last hundred years by a variety of agricultural and flood control projects. Stream hardening, channelization, and the removal of riparian vegetation have transformed some reaches of the stream into a waterway that closely resembles a storm sewer (Figure 1). The elimination or reduction of shade provided by riparian vegetation has encouraged the growth of channel-clogging California grass (*Brachia mutica*), wild sugarcane (*Saccharum officinarum*), and other vegetation that take up water and trap sediments (Figure 4). Dams and irrigation ditches have dramatically altered the natural flow of water in the stream. The result is that portions of Waimānalo Stream are now stagnant wetlands rather than free-flowing waters.

The headwaters of Kāne'ohe Stream lie in the steep cliffs (pali) that form the eastern side of the Ko'olau mountain range in the Kāne'ohe Bay watershed on the windward side of O'ahu. Kāne'ohe Stream itself is formed by the confluence of Kamo'oali'i Stream and Kapunahala Stream near Kamehameha Highway (Figure 3). Kapunahala Stream is the smaller of the two tributary streams. It is formed by the confluence of Punahala and Keapuka Streams. Kamo'oali'i Stream is the major tributary. Kamo'oali'i Stream is formed by the confluence of Luluku Stream and the discharge from the Ho'omaluhia Reservoir. Both Luluku Stream and the streams that feed into the Ho'omaluhia Reservoir drain mostly forested land, although the Ho'omaluhia Botanical Garden, the Ko'olau Golf Course, roads, and highways are important land uses in the watershed. Luluku Stream and its tributaries flow through part of the area occupied by the Likelike/H-3 highway interchange (Figure 3) but otherwise drain largely undeveloped and forested land.

The Kamo'oali'i Stream watershed covers an area of 11.2 km^2, and annual discharge of the stream is estimated to be 1.2×10^7 m^3 (Takasaki et al. 1969). The annual discharge from Kapunahala Stream has been estimated to be 3.9×10^6 m^3 (Takasaki et al. 1969). Hence the total annual discharge from Kāne'ohe Stream is about 1.6×10^7 m^3. Assuming that the ratio of stream discharge to watershed area is similar for Kamo'oali'i and Kapunahala Streams, the total watershed of Kāne'ohe Stream covers an area of 14.9 km^2, very similar to the area of the Waimānalo Stream watershed.

The Ho'omaluhia Reservoir was built for flood control after disastrous flooding of the Keapuka Subdivision of Kāne'ohe in 1965 and 1969. The earthen dam that created the reservoir was completed in 1980. Kamo'oali'i/Kāne'ohe Stream is hardened a short distance below the Ho'omaluhia Reservoir to the mouth of Kāne'ohe Stream. Our study focused on this hardened section of the stream, which flows through urbanized land in the town of Kāne'ohe.

MATERIALS AND METHODS

Water samples were taken at the locations shown in Figures 2–3. Waimānalo Stream was sampled along the Kahawai tributary and below the confluence of Kahawai and Waimānalo Streams near the mouth of the stream where it discharges into Waimānalo Bay. Most of the Waimānalo Stream stations were sampled a total of 10–12 times at roughly 3- to 4-week time intervals during the period February–October 2002. Kāne'ohe Stream sampling was carried out at roughly 3-week intervals during the period June–November 2002. Most Kāne'ohe Stream stations were sampled a total of nine times.

Waimānalo stations 2–5 and 7 lie along a hardened section of the stream that extends for a distance of approximately 0.8 km upstream and immediately downstream of Kalaniana'ole Highway. Station 1 lies immediately upstream of the hardened section. Station 6 is the effluent from an underground storm sewer that discharges beneath the Kalaniana'ole Highway bridge. Stations 7–9 lie at the beginning, midpoint, and end, respectively, of a stream restoration project carried out by the Waimānalo Watershed Project. Station 10 is at the head of the Waimānalo Stream estuary. In the Kāne'ohe Stream study, station 1 is located in a natural stream channel with no upstream hardening. Station 5 is the effluent from a spring that seeps into Kamo'oali'i Stream near the Likelike Highway culvert. Station 10 is immediately downstream of the hardened section of the stream in the head of the Kāne'ohe Stream estuary. The remaining stations are located along the hardened section of Kamo'oali'i/Kāne'ohe Stream.

Sampling was conducted irrespective of weather conditions. Average rainfall on the days of sampling was 0.26 cm and 0.17 cm at U.S. Weather Service stations HI-13 in Waimānalo and HI-16 in Kāne'ohe, respectively. These figures are 87% and 24%, respectively, of the average rainfall at those stations (http://www.prh.noaa.gov/pr/hnl/pages/hydrology.html). Most samples were collected during dry weather. Discharge from the storm sewer at Waimānalo station 6 was small during dry weather and apparently reflected groundwater seepage into a leaky sewer line. By far the wettest sampling day in Waimānalo was 16 March, when 2.5 cm of rain were recorded at HI-13. The wettest sampling day in Kāne'ohe was 26 July, when 0.66 cm of rain was recorded at HI-16.

Water samples were collected in 800-ml plastic bottles and immediately placed in an ice chest. Measurements of temperature, pH, and oxygen concentration were made in the field. Temperature was recorded to the nearest 0.1°C with a thermometer calibrated at 0°C (ice bath) and 100°C (boiling water). Oxygen concentrations were recorded with a dissolved oxygen meter (YSI model 58). pH was recorded to the nearest 0.1 using a portable pH meter (IQ Scientific model 3000). In the laboratory, the water samples were filtered through preweighed glass fiber filters (Whatman GFF) with a nominal porosity of 0.7 μm. The filters were dried in a drying oven at 105°C to constant weight. The filters were weighed on an analytical balance (Mettler model H20T) to the nearest 0.01 mg. Duplicates were run on random samples as a check on precision. Blanks were run by filtering 250 ml of distilled water through a filter. The weight of material collected on the filters ranged from a few milligrams to several tens of milligrams. The blank correction was less than 0.1 mg. The concentration of total suspended solids was calculated from the difference in the weights of the filter before and after filtering. Alkalinity measurements were made by titration of 50-ml aliquots of unfiltered water to pH 4.5 (American Public Health Association 1998).

The filtrate from the suspended solids filtration step was transferred to plastic bottles and processed for nutrient concentration measurements. The filtrates were frozen if not immediately analyzed. Concentrations of nitrate + nitrite (hereafter, nitrate), phosphate, and silicate were measured on the filtrate using colorimetric techniques on a Technicon Instruments AutoAnalyzer. The procedures used for the colorimetric assays adhered to those described in American Public Health Association (1998). Limits of detection were 0.5 μM for silicate and 0.1 μM for nitrate and phosphate. Concentrations of total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) were determined by first oxidizing the filtrates with an ultraviolet light photo-oxidation unit (Ace-Hanovia) and then assaying for nitrate and phosphate, respectively. Concentrations of particulate nitrogen (PN) and particulate phosphorus (PP) were calculated by assuming that the total suspended solids (TSS) contained 0.35% nitrogen and 0.11% phosphorus by weight (Laws and Ferentinos 2003). Concentrations of total nitrogen (TN) and total phosphorus (TP) were then calculated as TDN + PN and TDP + PP, respectively.

RESULTS

Before comparing results between stations, we first examined the distribution of data at each station to determine which parametric or nonparametric method would be best suited for the analysis. Hawai'i Department of Health (2000) water quality criteria for nutrients and suspended solids are based in part on geometric mean concentrations, the rationale being that the data are best described by a log-normal distribution function. If the data followed a log-normal distribution, the medians and geometric means would be identical. To test this hypothesis, we compared the geometric means and medians of the nutrient and TSS concentrations at the Waimānalo (Table 1) and Kāne'ohe (Table 2) sampling stations. Median silicate concentrations exceeded geometric mean silicate concentrations at 19 of 20 stations, a highly improbable result by random chance ($P = 4 \times 10^{-5}$ by a two-tailed test assuming a 50% chance that the median is greater than the geometric mean). Median nitrate concentrations exceeded geometric mean nitrate concentrations at 17 of 20 stations, again a highly improbable result by random chance ($P = 0.0026$). In the silicate and nitrate comparisons, the median values exceeded the geometric mean values by as much as a factor of 2. Using the same logic, however, there was no significant difference between median and geometric mean concentrations of TN, TP, and TSS. The best agreement between geometric means and medians occurred for TSS and TP, where the median equaled or exceeded the geometric mean at 8 and 10, respectively, of the 20 stations. If the median and geometric mean were identical, one

TABLE 1

Geometric Mean (GM) and Median (MN) Concentrations of TN, Nitrate, TP, TSS, and Silicate at Waimānalo Sampling Stations

	TN (μM)		Nitrate (μM)		TP (μM)		TSS (mg/liter)		Silicate (μM)	
Station	GM	MN	GM	MN	GM	MN	GM	MN	GM	MN
1	442	406	364	375	0.81	0.67	13.5	15.2	318	435
2	552	621	422	434	0.43	0.36	7.2	8.3	381	467
3	538	530	406	428	0.38	0.39	7.7	6.1	336	425
4	644	704	472	489	0.39	0.35	7.2	7.4	296	417
5	713	738	484	460	0.83	0.97	13.6	8.9	307	450
6	762	759	602	616	0.45	0.23	0.98	1.02	427	611
7	573	646	443	400	1.22	1.20	20	18	371	455
8	557	670	422	444	1.68	2.10	27	30	379	455
9	498	519	404	364	1.10	1.10	11	20	488	483
10	26.6	27.4	5	9	0.91	0.68	20	21	63	144

TABLE 2

Geometric Mean (GM) and Median (MN) Concentrations of TN, Nitrate, TP, TSS, and Silicate at Kāne'ohe Sampling Stations

	TN (μM)		Nitrate (μM)		TP (μM)		TSS (mg/liter)		Silicate (μM)	
Station	GM	MN	GM	MN	GM	MN	GM	MN	GM	MN
1	15.3	15.5	5.6	6.8	0.63	1.18	2.2	2.3	224	407
2	20.9	21.3	3.6	7.1	0.56	0.76	4.5	6.4	290	330
3	26.3	23.4	5.3	10.5	0.44	0.49	3.1	2.6	199	311
4	28.8	29.0	10.4	13.6	0.41	0.40	4.4	3.4	199	310
5	157	188	103	148	1.31	1.65	7.6	11.7	296	366
6	24.3	22.1	12.9	16.4	0.30	0.29	2.8	2.6	205	305
7	23.4	22.0	10.3	11.0	0.30	0.32	4.0	4.2	199	258
8	23.1	24.4	7.7	8.8	0.48	0.41	6.5	7.0	273	331
9	21.1	21.5	10.3	14.3	0.41	0.44	4.2	4.1	303	346
10	16.3	15.1	2.8	7.1	0.49	0.49	5.4	4.2	190	260

would be expected to exceed the other 50% of the time by random chance.

We concluded from this analysis that there was no single probability distribution function that characterized all the parameters we measured. We therefore opted to use the nonparametric Kruskal-Wallis (KW) test (Sokal and Rohlf 1981) to determine whether there were significant differences in water quality between stations. Based on the KW test, there was a highly significant difference in silicate concentrations between the 20 stations ($P = 3 \times 10^{-7}$). The stations fell into three groups. Group 1 consisted of all Kāne'ohe Stream stations, and group 2 consisted of all Waimānalo Stream stations except station 10. These two groups had geometric mean and median silicate concentrations of 238 and 313 μM (group 1) and 365 and 455 μM (group 2), respectively. The KW test indicated that the silicate concentrations differed significantly between these two groups ($P = 2 \times 10^{-11}$). Group 3 consisted of Waimānalo Stream station 10 (Table 1). Water at that station is brackish, and the silicate concentration is significantly reduced by the contribution of nearshore seawater, which has a silicate concentration less than 5 μM (Laws et al. 1999).

Based on the KW test, there was a highly significant difference ($P < 10^{-8}$) in nitrate and TN concentrations between stations. The stations logically fell into three groups. The first group consisted of Waimānalo station 10 and all Kāne'ohe stations except station 5. The second group consisted of all Waimānalo stations except station 10. The third group consisted of a single station, Kāne'ohe station 5. Geometric mean and median nitrate concentrations for these three groups were 6.7 and 9.8 μM (group 1), 429 and 456 μM (group 2), and 103 and 148 μM (group 3). Corresponding TN concentrations were 22.1 and 22.0 μM (group 1), 572 and 642 μM (group 2), and 157 and 188 μM (group 3). None of the geometric means satisfies Hawai'i Department of Health (2000) water quality criteria.

TSS concentrations were significantly different between stations ($P = 4 \times 10^{-9}$). In this case the stations logically separated into two groups, with the Waimānalo stations having the higher TSS concentrations ($P = 4 \times 10^{-8}$). Geometric mean and median TSS concentrations at the 10 Kāne'ohe stations were 4.2 and 4.1 mg liter^{-1}, respectively. Corresponding values for the Waimānalo stations were 9.7 and 10.2 mg liter^{-1}, respectively. Both geometric means satisfy Hawai'i Department of Health (2000) water quality criteria.

There was a significant difference in TP concentrations between all stations ($P = 8 \times 10^{-4}$), and again between all Waimānalo stations and all Kāne'ohe stations considered as two groups ($P = 0.0055$). Geometric mean and median TP concentrations at the 10 Kāne'ohe stations were 0.48 and 0.46 μM, respectively. Corresponding values for the Waimānalo stations were 0.72 and 0.75 μM, respectively. Both geometric means satisfy Hawai'i Department of Health (2000) water quality criteria.

Figures 5–8 show box-and-whisker plots of temperature, pH, dissolved oxygen concentration (DO), and DO as a percentage of saturation, respectively. The boxes show lower-quartile, median, and upper-quartile values. The whiskers show the range of values, except in the case of outliers, which are indicated by +. Temperature in Luluku Stream (Kāne'ohe station 1) was 4–7°C cooler than at the other Kāne'ohe stations. Although stream hardening and the absence of shade along the course of Kamo'oali'i/Kāne'ohe Stream undoubtedly contributed to this differential, an important additional factor is the temperature of the overflow from Ho'omaluhia Reservoir. Sampling of the water immediately downstream of the spillway revealed an average temperature of 25.0°C with a standard deviation (SD) of ±1.6°C. However, median temperatures below the Likelike Highway were even higher (27–28°C), with excursions above 30°C. In Waimānalo Stream the lowest median temperature was again at the station farthest upstream. Upper-quartile temperatures rose steadily from station 1 to station 5 and exceeded 28°C below station 2. The temperature of the discharge from the storm sewer (station 6) was anomalously low, but upper quartile temperatures in the stream channel again rose steadily from station 7 to station 9, and peak temperatures reached 32°C. Hawai'i Department of Health (2000) water quality criteria specify that stream temperature shall not deviate by more than 1°C from ambient conditions. This condition is clearly violated in the hardened sections of both Kāne'ohe and Waimānalo Streams.

The pattern in pH values also reflected the influence of hardening. In Kāne'ohe Stream the pH values in the stream channel increased steadily with distance downstream. The lowest median pH values of 6.6 and 7.1 were recorded in Luluku Stream and the spring at station 5, respectively. Upper-quartile values in the stream channel exceeded 8.0 at all stations within the hardened section of the stream, and upper-quartile pH values exceeded 8.5 at stations 7–9. In Waimānalo Stream the median pH values in the stream channel also increased steadily from station 1 to station 5 and exceeded 8.0 at stations 4 and 5. However, median pH values dropped along the restored steam channel from stations 7 to 9. The increase in pH between stations 9 and 10 probably reflects the influence of seawater at station 10. The pH of surface seawater in the vicinity of Hawai'i lies in the range 8.0–8.1 (Joint Global Ocean Flux Study 2002).

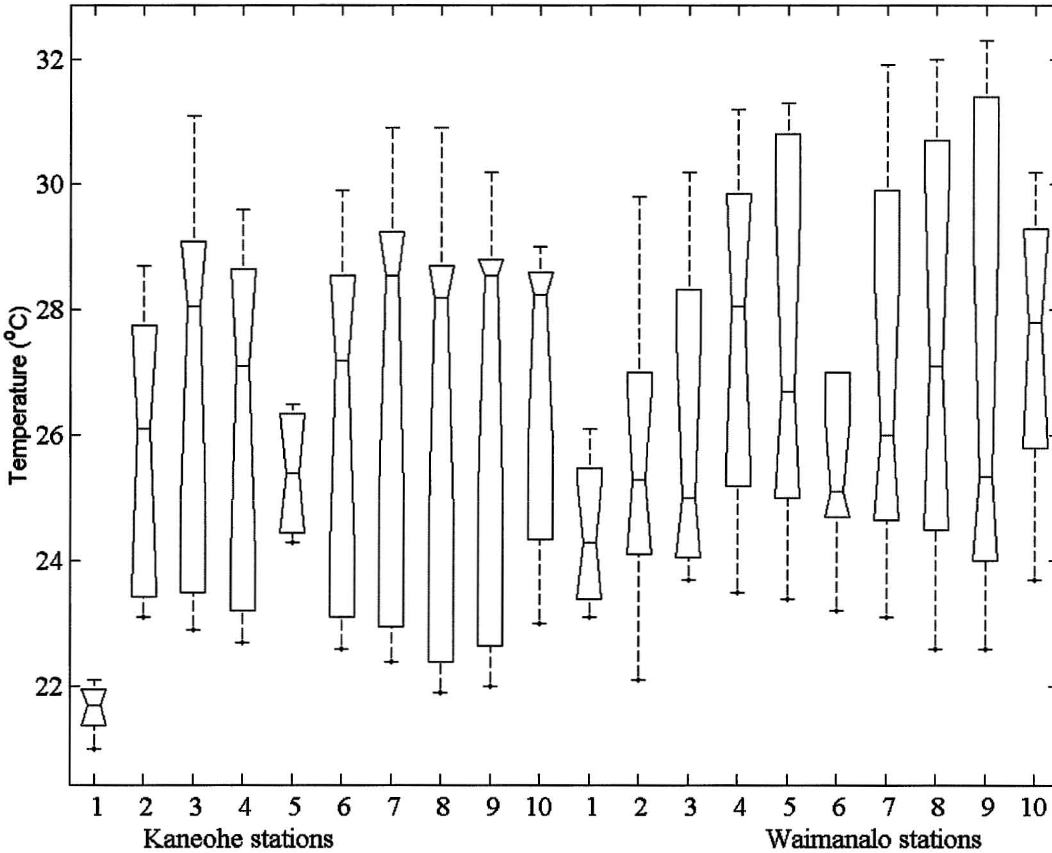

FIGURE 5. Box-and-whisker plot of stream temperatures at Kāne'ohe and Waimānalo stations. Boxes indicate lower-quartile, median, and upper-quartile values. Whiskers extend to lowest and highest values.

Oxygen concentrations displayed somewhat different patterns in Kāne'ohe and Waimānalo Streams. By far the lowest O_2 concentrations occurred in the spring that seeps into Kamo'oali'i Stream at station 5. Median concentrations there were about 3 ppm (Figure 7), which corresponds to less than 40% of saturation (Figure 8). Median O_2 concentrations at the other Kāne'ohe stations were all above 80% saturation. The Hawai'i Department of Health (2000) water quality standard for oxygen states that the O_2 concentration should not be less than 80% of saturation. Lower-quartile O_2 concentrations at stations 7 and 10 were both less than 80% of saturation. In Waimānalo Stream, the O_2 concentrations at station 1 were 5–6 ppm, lower than at any other Waimānalo station. These corresponded to about 70% of saturation. The O_2 concentrations rose dramatically between stations 1 and 2 and continued to rise to stations 4 and 5, where they averaged about 11 ppm or 140% of saturation. O_2 concentrations were anomalously low (~6 ppm) in the storm sewer discharge and declined steadily between stations 7 and 10 (i.e., downstream of the hardened section of the stream). Median concentrations at stations 9 and 10 were below the Hawai'i Department of Health 80% criterion.

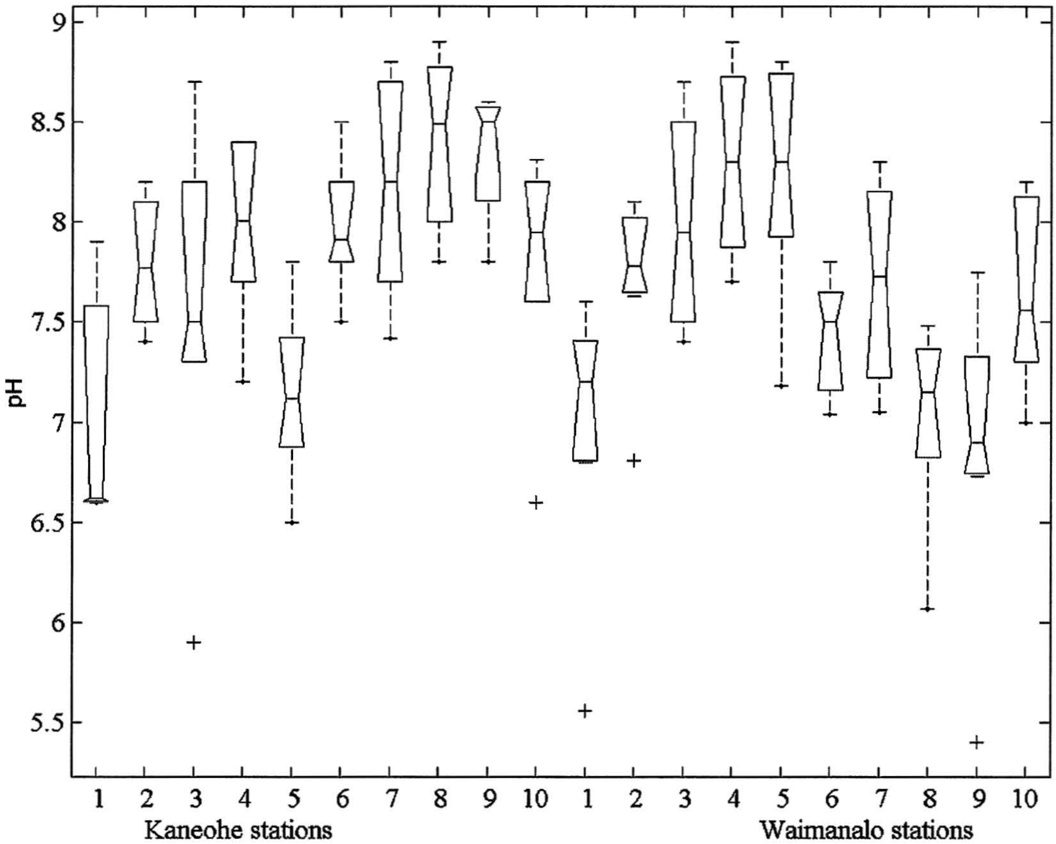

FIGURE 6. Box-and-whisker plot of stream pH values at Kāne'ohe and Waimānalo stations. Boxes indicate lower-quartile, median, and upper-quartile values. Whiskers extend to lowest and highest values. + indicates outlier.

DISCUSSION

Alterations to habitat as a result of stream hardening and land use in the Kāne'ohe and Waimānalo watersheds are evident in a variety of ways. The temperature regime in the streams has clearly been altered by the wide, flat concrete channels and the absence of shade. Stream temperatures upstream of the hardening were 22–24°C. Within the hardened sections, temperatures rose to 26–28°C (Figure 5). This is clearly a violation of Hawai'i Department of Health (2000) water quality criteria. The wide, flat bottom of the hardened stream bottoms is certainly part of the problem. At Waimānalo station 1 (natural channel bottom) the depth at the thalweg averaged 20 ± 8 cm. At stations 2–5 the corresponding depth was only 3 ± 1 cm. Restoration efforts (Figure 9) have created a low-flow channel below the Kalaniana'ole Highway culvert. The average water depth at stations 7–10 was 12 ± 2 cm. Nevertheless, the absence of shade resulted in water temperatures of 26–27°C at these latter stations. A qualitatively similar physical situation exists along the hardened portion of Kamo'oali'i/Kāne'ohe Stream. The depth at the thalweg at Kāne'ohe station 1 averaged 24 ± 10 cm. At the hardened stations (2–4 and 6–10) the water column was only about half as deep. The depth averaged 13 ± 4 cm.

Flood control is certainly an important consideration in any urban stream, but flood

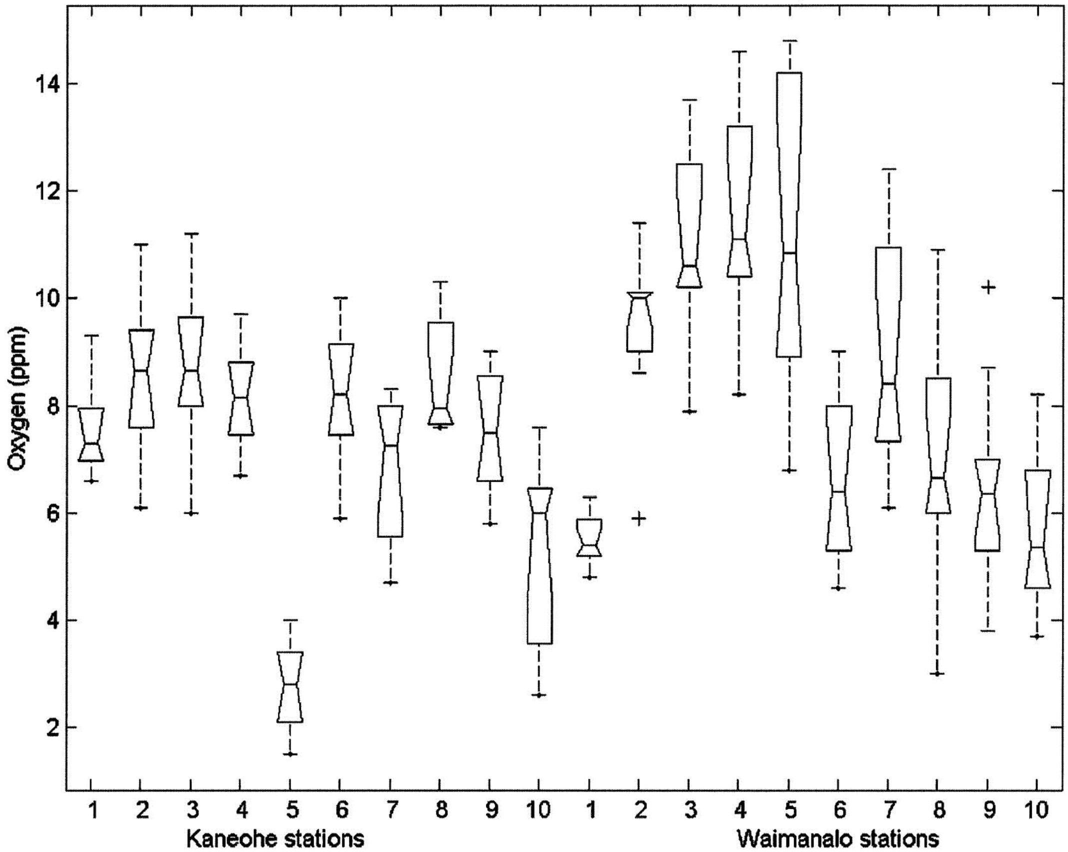

FIGURE 7. Box-and-whisker plot of O_2 concentrations at Kāne'ohe and Waimānalo stations. Boxes indicate lower-quartile, median, and upper-quartile values. Whiskers extend to lowest and highest values. + indicates outlier.

control does not require that the bottom of the stream channel be lined with concrete or that overhanging riparian vegetation be removed. Figure 10, for example, shows a portion of Mānoa Stream near Pāwaina Street in upper Mānoa Valley, a residential suburb of Honolulu. The natural stream channel has been left intact, and there is an abundance of riparian trees to shade the stream. Vertical revetments of stone and concrete contain the flood plain along this portion of the stream, but there is clearly a low-flow channel, a flood plain, and an abundance of riparian vegetation. Figure 10 contrasts sharply with Figure 1. Figure 10 demonstrates that it is possible to provide flood control without destroying the habitat and functionality of an urban stream.

The patterns in pH and O_2 in Kāne'ohe and Waimānalo Streams appear to reflect a combination of photosynthetic and respiratory activities. Carbon dioxide combines with water to form carbonic acid. Through uptake of CO_2, photosynthesis reduces the concentration of carbonic acid and hence drives up the pH. Increases in pH could also result from chemical interactions between the concrete and water (e.g., dissolution of calcium carbonate). However, we found no evidence of an increase in alkalinity along the hardened sections of the streams. In fact, alkalinities actually decreased between Waimānalo sta-

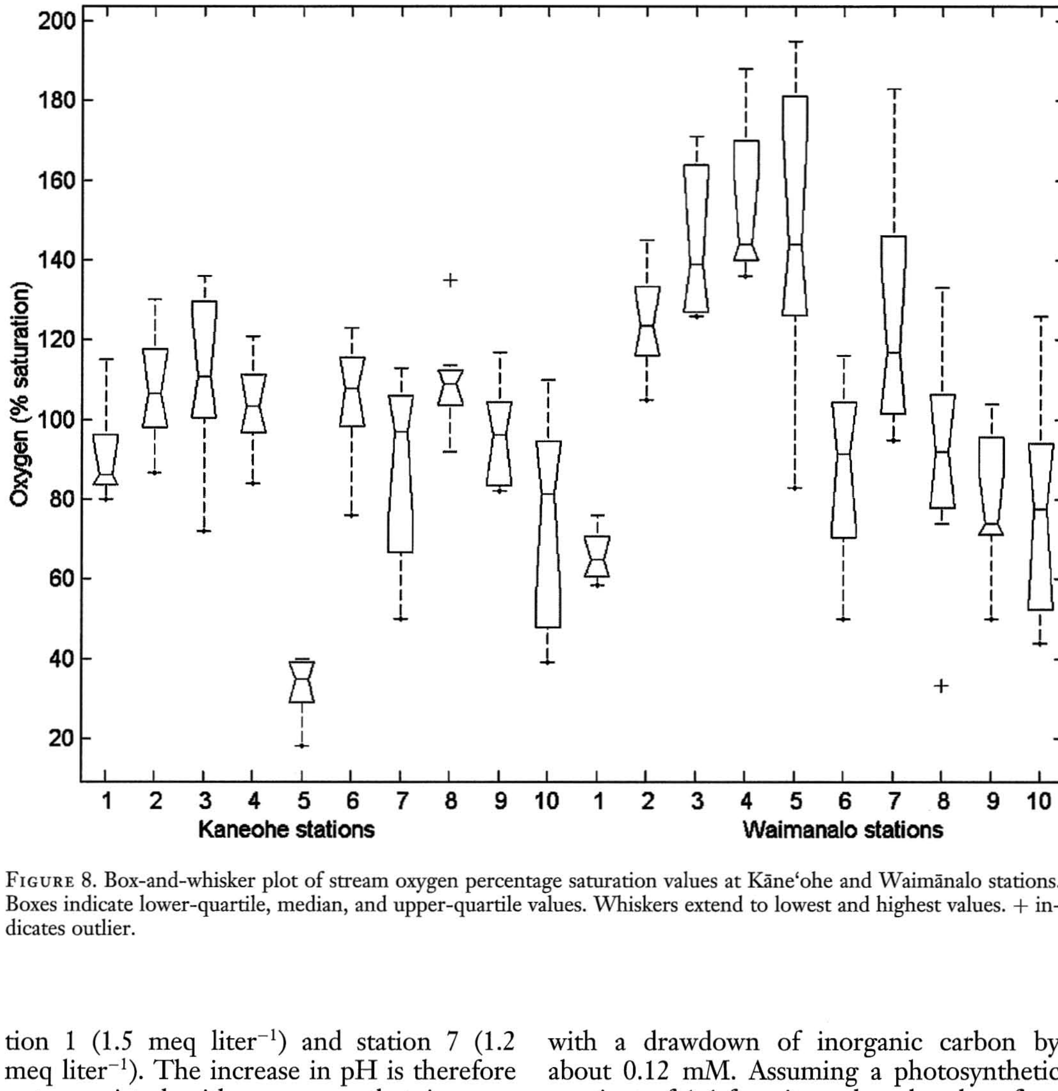

FIGURE 8. Box-and-whisker plot of stream oxygen percentage saturation values at Kāne'ohe and Waimānalo stations. Boxes indicate lower-quartile, median, and upper-quartile values. Whiskers extend to lowest and highest values. + indicates outlier.

tion 1 (1.5 meq liter^{-1}) and station 7 (1.2 meq liter^{-1}). The increase in pH is therefore not associated with processes that increase alkalinity. We thus believe that the increase in pH apparent along the hardened sections of both streams (Figure 6) is due to photosynthetic activity. This photosynthetic activity translates into a dramatic rise in O_2 concentrations from stations 1 through 5 in Waimānalo Stream.

Using the equilibrium constants for the carbonate system given by Riley and Chester (1971), it is straightforward to show that in a closed freshwater system at 25°C with a constant carbonate alkalinity of 1.2 meq liter^{-1}, a rise in pH from 7 to 8 would be associated with a drawdown of inorganic carbon by about 0.12 mM. Assuming a photosynthetic quotient of 1.4 for nitrate-based carbon fixation (Laws 1991), this would translate into a rise in the O_2 concentration of 5.4 ppm. This is comparable to the rise in O_2 concentration between stations 1 and 5 in Waimānalo Stream (Figure 7). Why a comparable rise in O_2 concentration does not occur in the case of Kāne'ohe Stream is unclear, but the fact is that neither stream is a closed system. The very low O_2 concentration in the spring water at Kāne'ohe station 5 suggests that groundwater seeping into the stream may suppress the rise in O_2 that would otherwise result from photosynthetic activity. Likewise, the

FIGURE 9. A stream restoration project under way in Waimānalo Stream below a hardened section of the stream.

low-oxygen storm drain discharge at station 6 in Waimānalo may contribute to the decline in O_2 concentration between Waimānalo stations 5 and 7 (Figure 7).

Headwater streams are generally heterotrophic systems (Rankin et al. 1999:14). Hawaiian streams are by default all low-order streams because of the short distance from their headwaters to their mouths. One might therefore expect to find that Hawaiian streams consume oxygen and organic matter, and this appears to be the case along the section of Waimānalo Stream where there is a natural streambed (i.e., between stations 7 and 10 [Figure 7]). The sediments are an obvious place for heterotrophic activity to occur, and the absence of sediments in a stream with a flat concrete bottom tends to shift the metabolism of the stream toward autotrophy. In the case of Kāne'ohe and Waimānalo Streams, this tendency is further stimulated by the absence of shade.

Given the low O_2 concentrations within stream sediments, the consumption of organic matter that occurs in the sediments is often accompanied by denitrification. The importance of this process in the case of Waimānalo Stream is dramatically illustrated by examining the relationship between silicate and nitrate concentrations in hardened and natural sections of the stream (Figure 11). The straight line was drawn through median data from the hardened sections of the stream and the oceanic endpoint, which occurs at silicate and nitrate concentrations of about 1.0 μM and 0.01 μM, respectively (Laws et al. 1999, Joint Global Ocean Flux Study 2002). If nitrate concentrations in the stream were reduced merely by dilution with seawater, all data would be expected to lie near the regression line. In fact all data from the estuarine region (stations 10–12) lie well below the regression line, as do the median values from stations 7–9. This pattern is very

FIGURE 10. A section of Mānoa Stream in upper Mānoa Valley near Pāwaina Street.

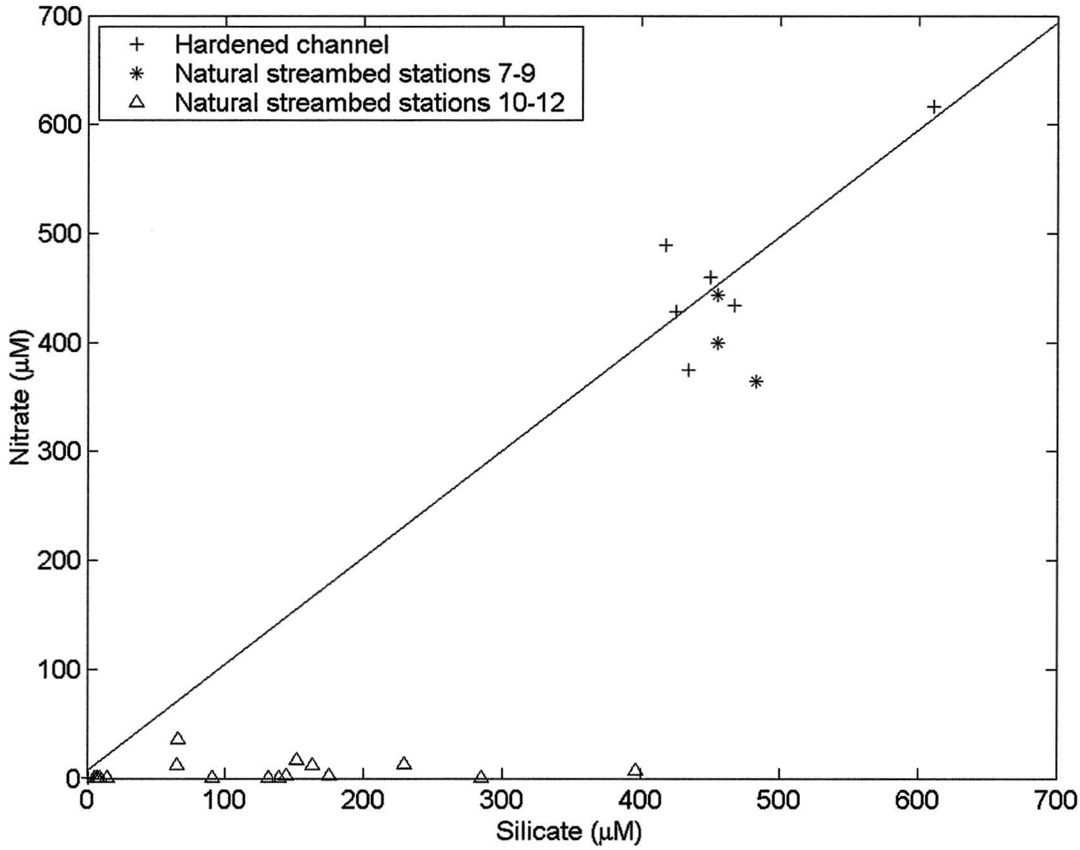

FIGURE 11. Silicate versus nitrate concentrations in Waimānalo Stream. The straight line is a model II geometric mean regression line fit to the data from the hardened channel and the oceanic endpoint near the lower left-hand corner of the plot. Data from the hardened stations and stations 7–9 are median values. Data from stations 10–12 (estuary) are individual data points.

likely due to biological uptake of nitrate, with most of the uptake evidently occurring between stations 9 and 10. Although photosynthetic uptake of nitrate may well occur in the channel below Waimānalo station 7, the fact that O_2 concentrations decline between stations 7 and 10 (Figure 7) indicates that the system is heterotrophic, not autotrophic. Denitrification is an obvious mechanism for heterotrophic metabolism to reduce nitrate concentrations, but denitrification can occur only in the virtual absence of O_2. Because the water column itself contains in excess of 4 ppm O_2 (Figure 7), the denitrification is very likely occurring in the sediments of the natural streambed. Because the hardened sections of the channels contain virtually no sediments, removal of nitrate by this mechanism is precluded in the hardened sections of the stream.

The high nitrate concentrations in the hardened channels of Waimānalo Stream and to a much lesser extent Kāne'ohe Stream cannot be attributed entirely to the absence of stream sediments and associated metabolic processes. Both streams experience remarkably high inputs of nitrate from allochthonous sources. The storm sewer at station 6 in Waimānalo Stream contains in excess of 600 µM nitrate, and the spring that seeps into

Kāne'ohe Stream at station 5 contains more than 100 μM nitrate. The ability of both streams to accommodate these inputs, however, is compromised by the absence of a natural streambed.

Both Waimānalo Stream and Kāne'ohe Stream discharge into coastal-zone coral reef ecosystems. Do the high nitrate concentrations associated with hardening of these streams adversely affect nearshore corals? Conventional wisdom is that inorganic nutrient enrichment adversely affects coral reefs (Bell 1992, Dubinsky and Stambler 1996, Lapointe 1997). Probably the best-known study of the adverse effects of nutrient enrichment on coral reefs comes from Kāne'ohe Bay (Smith et al. 1981). Nevertheless, Atkinson et al. (1995) have shown from a study of hermatypic corals grown in high-nutrient seawater at the Waikīkī Aquarium that the growth of corals is not inhibited at nitrate concentrations as high as 5 μM. The adverse effect of nutrient enrichment on the coral reefs in Kāne'ohe Bay appears to have been indirect and caused in part by the stimulation of phytoplankton populations, which reduced light transmission through the water column and provided food for benthic filter feeders such as barnacles, sponges, tunicates, and zoanthids (Laws 2000). Nutrient enrichment can adversely affect coral reefs, but the results of nutrient enrichment will depend very much on the physics of the system. Plankton blooms will not occur unless the residence time of the water is sufficient to permit their development. The adverse effects of the sewage discharges into Kāne'ohe Bay were eliminated by moving the sewer outfalls to an open-ocean site, where currents and mixing minimized the impact of the nutrients in the wastewater on the plankton community (Laws and Terry 1983). Miller et al. (1999) concluded from their own work and the study of Larned and Atkinson (1997) that the nutritional status of benthic algae is more sensitive to the depletion of the boundary layer around algal thalli by water movement and turbulence than to the bulk nutrient concentration in the water. It seems safe to conclude that streams discharging low-nutrient water will have no adverse effects on coral reefs. Hardened streams discharging high-nutrient water have the potential to adversely affect coral reefs, but the actual impact will depend on other factors, including in particular the physics of the nearshore environment.

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